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top2008 Conference Summary

S. Willenbrock

Department of Physics, University of Illinois at Urbana-Champaign
1110 West Green Street, Urbana, IL 61801

Abstract

This is a summary of the talks presented at the International Workshop on Top Quark Physics (top2008) held in Elba, Italy, May 18-24, 2008.

1 Introduction

We heard 48 talks at this workshop, consisting of 1571 slides, and I am supposed to summarize it all in 60 minutes. I will emphasize the Tevatron, since it is producing all the top-quark physics results right now. The LHC will soon have its day, and will eventually dominate this conference series. I will mostly refer to the talks at the workshop (in parentheses), where a more complete set of references can be found.

On April 1, 2008, Fermilab announced that it has revised the Tevatron schedule so that the next shutdown will occur in Spring 2009. This would allow the machine to run until the end of FY2010 with just a single shutdown. Although the Tevatron is currently approved to run only until the end of FY2009, the laboratory has requested a one-year extension. A decision on this request has not yet been made. Including the extension, an integrated luminosity of over 8 fb^{-1} could potentially be delivered to the experiments (Glenzinski).

The LHC will begin operations later this year, and could deliver on the order of 10 pb^{-1} to the experiments at a collider energy of 10 TeV. The expectation is that the collider energy will be increased to the full 14 TeV in 2009, and will deliver an integrated luminosity on the order of 1 fb^{-1} . There is still a lot of uncertainty in the schedule, as we are reminded by the recent problem with the plug-in modules that connect the dipole magnets together (Bailey). That problem has been solved, but there may be more bumps in the road. The important thing is that the LHC eventually works, which will be an amazing feat.

ATLAS and CMS have made tremendous progress, and are getting ready to take their first data (Acosta, Schiavi). It is amazing to see images of the CMS cavern, empty just two years ago, now filled with the enormous detector. Cosmic ray data whets our appetite for the first collider data.

2 $t\bar{t}$ cross section

The best single measurement of the $t\bar{t}$ cross section comes from the lepton plus jets channel with one or more b tags (Castro, Sharry),

$$\begin{aligned}\sigma(t\bar{t}) &= 8.2 \pm 0.5 (\text{stat}) \pm 0.8 (\text{sys}) \pm 0.5 (\text{lum}) \text{ pb (CDF)} \\ \sigma(t\bar{t}) &= 8.1 \pm 0.5 (\text{stat}) \pm 0.7 (\text{sys}) \pm 0.5 (\text{lum}) \text{ pb (D0)}.\end{aligned}$$

The D0 experiment has also made a measurement of the cross section in the τ +lepton and τ +jets channels (Sharry). Although it is not as accurate as the best measurements, it is impressive that such a measurement can be made. Keep in mind that a little over 20 years ago, the tau lepton was one of the sources of the “monojets” (not to be confused with the top-quark monojets referred to by Chevallier) seen by the UA1 experiment [1]. To quote the abstract of that paper, “We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet ...” We now recognize this as $W \rightarrow \tau\nu$, but at the time it was thought that it might be new physics. It is difficult to predict what things will puzzle us when we begin the operation of the LHC, but it is hard to imagine that there won’t be some confusion.

The measurements of the $t\bar{t}$ cross section are in good agreement with the predictions of next-to-leading-order (NLO) QCD. Theorists have been working hard to go beyond NLO,

and to estimate the uncertainties in the prediction (Mangano). The uncertainty from the parton distribution functions (PDF's) is quite small, around 6% for the Tevatron and 3% for the LHC according to CTEQ6.5, but it is perplexing that MRSTW-06 gives an uncertainty about half that amount. Even worse, the central values of the cross section calculated from the two PDF's differ by about 6% at the LHC, which is nearly twice the uncertainty from the PDF's. This needs to be sorted out.

Theorists are making progress towards a full NNLO calculation of the $t\bar{t}$ cross section, but there is still a ways to go (Mangano). In the meanwhile, there exist partial NNLO calculations. One recent calculation shows greatly reduced scale dependence, but this might be an artifact of equating the renormalization and factorization scales [2]. Recall that the former has to do with ultraviolet physics while the latter is related to collinear physics, so they are logically independent.

I would like to raise a separate issue, which is whether we should attach any significance to scale dependence at all, in particular whether we should use it to estimate theoretical uncertainties [3]. Consider a very basic process, Z production at the Tevatron. At leading order (LO), the cross section is predicted to be around 5.8 nb, with almost no scale dependence. The NLO cross section is about 7 nb, well outside of the range of the LO scale dependence; it also has almost no scale dependence. It agrees well with the NNLO cross section, as well as with the measured cross section. This suggests that one should take the uncertainty associated with scale dependence with a grain of salt, since it is misleading even in this very basic case.

Theorists have also calculated the NLO electroweak corrections to the $t\bar{t}$ cross section, and they are generally very small (Si). However, the corrections becomes significant, of order 10%, when considering top quarks at transverse momenta greater than 1 TeV at the LHC.

The cross section for $t\bar{t} + 1$ jet has also been calculated at NLO, and shows the usual reduction in scale dependence compared with LO (Uwer). The forward-backward asymmetry (also present in inclusive $t\bar{t}$ production [4]) at the Tevatron shows a large NLO correction, well outside the scale uncertainty of the LO calculation. Given my remarks above, I am not concerned about this, but the authors are currently considering whether there is an observable that is more stable under radiative corrections.

The LHC will be a top factory, and a top-quark signal is expected already in the first 10 pb⁻¹ (Cobal and Tsirigkas). It is anticipated that the $t\bar{t}$ cross section will be measured with an uncertainty of 5-10% (systematics dominated) in the first 100 pb⁻¹.

3 Top-quark mass

The top-quark mass is now known with remarkable precision, $m_t = 172.6 \pm 1.4$ GeV. I consider it a great success that the central value of the measured mass has not moved very much from its present value, going all the way back to the first measurement [5]. To convince you that this is nontrivial, consider the case of the third-generation charged lepton, the tau, whose mass has moved significantly over the years [6]. The consistency of the measured mass with the indirect mass extracted from precision electroweak data is another remarkable achievement, and gives us great confidence in the standard electroweak theory.

There was quite a bit of discussion of the top-quark mass definition at the workshop,

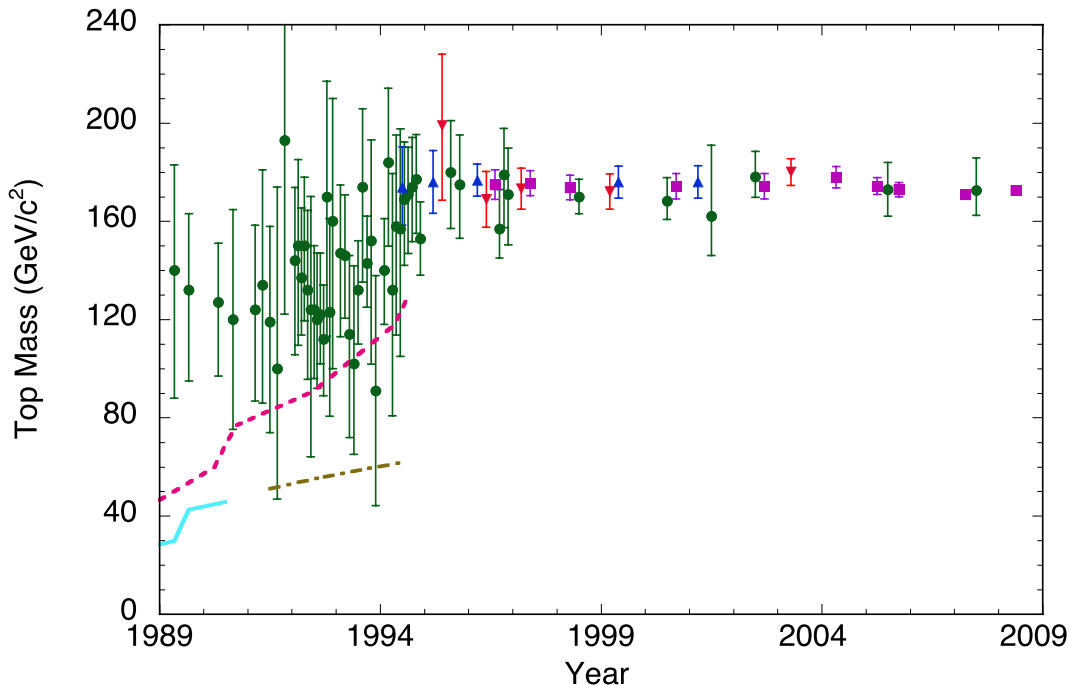


Figure 1: The central value of the top-quark mass has remained remarkably stable over the years, while the uncertainty has decreased dramatically [7].

so I'd like to pause here to review what we mean by a quark pole mass (Glenzinski). The propagation of a physical particle, such as an electron, is described in quantum field theory by a propagator, which is proportional to $1/(p^2 - m^2)$, where p is the particle's four-momentum. This propagator has a simple pole, in the language of complex analysis, at $p^2 = m^2$, and hence this mass is called the pole mass; for the electron, its value is $m = 0.511$ MeV. A quark propagator is similarly described. However, quarks are always confined, so there is really no such thing as a freely propagating quark, and hence the pole mass is not really physical. Since the scale of confinement is $\Lambda_{\text{QCD}} \approx 200$ MeV, the pole mass is only defined up to an ambiguity of order Λ_{QCD} . Thus we arrive at a definition of a quark pole mass: it's the mass the quark would have in the absence of confinement. Unfortunately, we cannot simply turn off confinement, so a quark pole mass is inherently ambiguous (of order Λ_{QCD}).

In all the calculations that are used to extract the top-quark mass from the experimental data, the top-quark propagator is described in the standard way (also including the width of the top quark). Hence the top-quark mass that we extract from experiment is the pole mass. Since the present uncertainty is large compared with Λ_{QCD} , we ignore the inherent ambiguity in the pole mass.

An idealized study suggests that the dependence of the top-quark mass extracted at the Tevatron on the hadronization (confinement) model has a non-perturbative component that is about 500 MeV, consistent with an ambiguity of order Λ_{QCD} in the pole mass (Wicke).

As with the $t\bar{t}$ cross section, the best measurements of the top-quark mass come from the lepton plus jets channel (van Remortel, Renkel),

$$\begin{aligned}
m_t &= 171.4 \pm 1.5 \text{ (stat + JES)} \pm 1.0 \text{ (sys)} \text{ GeV (CDF)} \\
m_t &= 172.2 \pm 1.1 \text{ (stat)} \pm 1.6 \text{ (sys + JES)} \text{ GeV (D0)}
\end{aligned}$$

where JES = Jet Energy Scale. The combined CDF and D0 mass measurement, $m_t = 172.6 \pm 1.4$ GeV, has an uncertainty that is approaching Λ_{QCD} , and could reach 1.0 GeV by the end of Run II (Glenzinski). At the LHC, the statistical uncertainty will be negligible, and the signal/background ratio is significantly greater than at the Tevatron, so one could contemplate a measurement with an accuracy of even less than 1.0 GeV (Sjolin and Wolf). Along with accurate knowledge of the jet energy scale, this would require taking the effects of confinement into account quantitatively.

There is no reason in principle that this could not be done. In fact, it has already been achieved for the proposed ILC, where a scan of the $t\bar{t}$ threshold could be used to measure the top-quark mass to an accuracy of 75 MeV (Juste). This is not the pole mass, but rather a short-distance mass that is free of the ambiguity of order Λ_{QCD} that plagues the pole mass.

Recently attention has turned to measuring the top-quark mass at the ILC above the $t\bar{t}$ threshold (Hoang). This is closer in spirit to the situation at the Tevatron and the LHC, although it is simpler since the initial state is colorless. Using a series of effective field theories, it has been shown how to isolate the nonperturbative contribution to the top-quark mass into a universal soft function that can be extracted from data. Perhaps something similar can be developed for hadron colliders.

I would like to speculate that one might be able to do even better. The top quark is produced on a very short time scale, of order m_t^{-1} , and propagates for a time scale of order $1/\Gamma_t$ before it decays to a W boson and a b quark. Only later, on a time scale of order $1/\Lambda_{\text{QCD}}$, does the process of hadronization (confinement) of the b quark take place. That means that the W boson is emitted well before the effects of confinement are felt. Thus

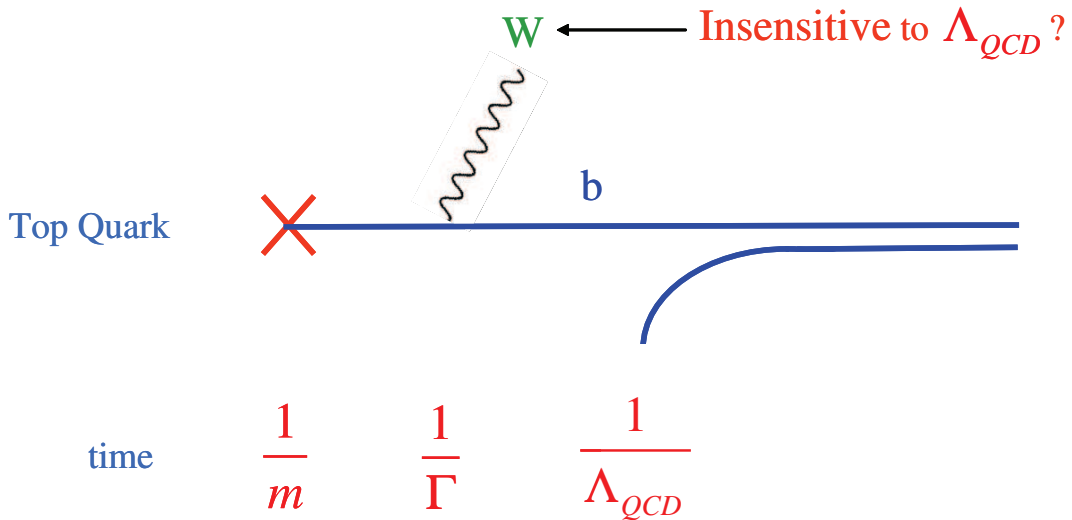


Figure 2: The top quark decays before it feels the effects of nonperturbative QCD (confinement).

the decay products of the W boson may be insensitive to the effects of confinement, and by studying them we might be able to extract the top-quark mass with less dependence on the quantitative details of confinement [8]. Indeed, there are studies of the top-quark mass from the lepton p_T spectrum (Giokaris), or from the lepton plus $J/\psi \rightarrow \ell^+\ell^-$ spectrum (Sjolin and Wolf), at the LHC. Perhaps these approaches will prove to be fruitful to reduce the quantitative effects of confinement.

Incidentally, this argument also demonstrates why it is not possible to avoid the ambiguity in the top-quark pole mass of order Λ_{QCD} , even though the top quark decays before it hadronizes. The top-quark mass is reconstructed from the invariant mass of the W boson and the b quark, but because the b quark hadronizes, this invariant mass is unavoidably ambiguous (of order Λ_{QCD}) [9].

4 Single top

Single top quarks are produced via the weak interactions via three processes, dubbed s -channel, t -channel, and Wt associated production (Jabeen, Lueck). While $t\bar{t}$ production can easily be separated from backgrounds in the lepton plus four jets mode (with one or more b tags), distinguishing single top production in the lepton plus two jets mode (with one or more b tags) requires a more sophisticated analysis, because the backgrounds are much more severe. It is amazing that the separation can be done at all. Both CDF and D0 have made measurements of the single-top cross section,

$$\begin{aligned}\sigma(t) &= 2.2 \pm 0.7 \text{ pb (CDF)} \\ \sigma(t) &= 4.7 \pm 1.3 \text{ pb (D0)}\end{aligned}$$

in good agreement with the standard-model prediction with $|V_{tb}| = 1$. Both experiments have made a first attempt to separate the s -channel and t -channel signals (Lueck), something we will see more of as the integrated luminosity mounts. Using their cross-section measurements, both experiments have extracted a value for $|V_{tb}|$,

$$\begin{aligned}|V_{tb}| &= 0.89 \pm 0.14 \text{ (exp)} \pm 0.07 \text{ (theory) (CDF)} \\ |V_{tb}|^2 &= 1.72^{+0.64}_{-0.54} \text{ (D0)}.\end{aligned}$$

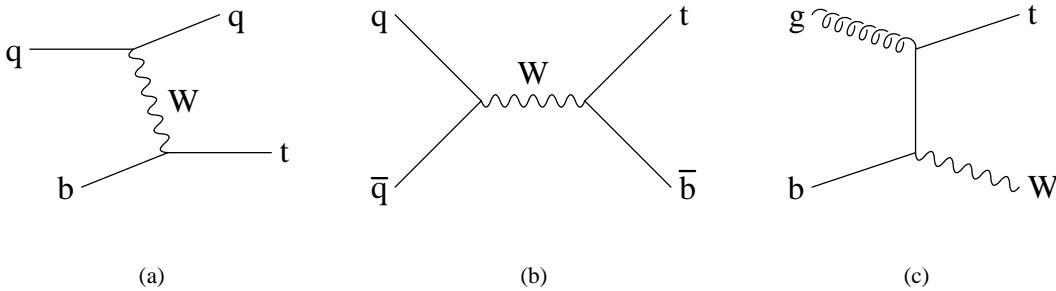


Figure 3: Single top quarks are produced via the t -channel, s -channel, and Wt associated production processes.

Ideally this information will be incorporated into a global fit of the CKM matrix. In this sense, we are now members of the CKM family. However, we need to think about what assumptions we are making. Since single-top production is dominated by the t -channel process, we usually assume that the initial parton is a b quark that gets converted into a top quark via the weak interaction, with a rate proportional to $|V_{tb}|^2$. However, it is also possible that the initial quark is a s or d quark, in which case the rate is proportional to $|V_{ts}|^2$ or $|V_{td}|^2$, respectively (Frederix). Thus we can use the measured cross section to constrain the parameter space of $|V_{tb}|, |V_{ts}|, |V_{td}|$. This is in the same spirit as constraining the $\bar{\rho}, \bar{\eta}$ plane (Bucci).

Despite this, one often wants to just quote a value for $|V_{tb}|$, and it is important to consider the minimum set of assumptions that allows one to do this. One could say that the assumption is that there are just three generations. While there is nothing wrong with that, there is a weaker assumption that one can make. If we simply assume that $|V_{tb}| \gg |V_{ts}|, |V_{td}|$ (with no assumptions about the number of generations), then single-top production is dominated by the t -channel process with an initial b quark, which is proportional to $|V_{tb}|^2$.

Theorists have been working hard to make accurate predictions for single-top production. All three processes have been calculated at NLO, including decays of the top quark and spin correlations (Tramontano). Electroweak corrections have also been calculated and, as in the case of $t\bar{t}$ production, the corrections are very small except for high- p_T top quarks, in which case the corrections are of order 10% at the LHC (Mirabella). The idea that one could observe single-top photoproduction at the LHC was discussed (Ovyn).

Single-top production will be observable at the LHC with around 10 fb^{-1} , including the first observation of Wt associated production. The s -channel process will be the most challenging to observe at the LHC (Cristinziani and Petrucciani).

5 Anomalous couplings

We heard a great deal about anomalous top-quark weak interactions at this workshop (Aguilar-Saavedra, Brandt, Jabeen, Juste, Shabalina, Spiga, Veloso). These are usually parameterized in terms of a vertex function that describes the Wtb vertex, assuming the top and bottom quarks are on shell;

$$\Gamma^\mu = -\frac{g}{\sqrt{2}}V_{tb} \left(\gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right)$$

where $P_{L,R} = (1 \mp \gamma_5)/2$. This is the most general vertex function consistent with Lorentz invariance for on-shell top and bottom quarks. The W boson may be off-shell with virtuality p_W^2 , and the form factors $f_{1,2}^{L,R}$ are unknown functions of p_W^2 . If we allow the top and bottom quarks to be off shell, the vertex function becomes much more complicated (Aguilar-Saavedra). There are sixteen additional form factors, and all form factors are unknown functions of p_W^2, p_t^2, p_b^2 .

There is an alternative approach based on the concept of an effective field theory [10]. In this approach, one accepts the standard electroweak theory as the correct zeroth-order approximation, and parameterizes physics beyond the standard model in terms of higher-dimension operators, suppressed by inverse powers of a large mass scale $\Lambda \gg M_W$. The

leading higher-dimension operators are those of the lowest dimensionality, since they are suppressed by the least inverse powers of Λ . These leading operators are of dimension six, so the effective Lagrangian is

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i (c_i \mathcal{O}_i + h.c.)$$

where \mathcal{O}_i are the dimension-six operators. There are many such operators, but only three of them are expected to be significant if the physics beyond the standard model is a weakly-coupled gauge theory, and one of those three is already very constrained by $b \rightarrow s\gamma$. By comparing data with theory one can put upper bounds on the coefficients c_i/Λ^2 . Although this has not been the approach that has usually been used for anomalous couplings, I think it is a lot cleaner, and I believe we will be seeing more of it in the future.

6 Tools for top

The number of tools available to us for top-quark physics (and collider physics in general) has grown enormously over the years, and they have become ever more sophisticated (Maltoni). There are three broad classifications of codes that use parton showers (PS): Matrix Element plus PS (Herwig, Pythia, etc.); Matrix Element plus PS plus Merging (Alpgen, MadGraph, Sherpa); and NLO plus PS (MC@NLO, POWHEG). There is no code that includes NLO plus PS plus Merging, although that is probably within reach. These codes are incredibly useful for comparing theory with experiment.

Although these codes are generally accurate, they are not perfect, and by comparing different codes we can appreciate their strengths and weaknesses, and hopefully improve them. One example relevant to top-quark physics is the rapidity distribution of the hardest jet (not from top decay) in $t\bar{t}$ +jets events. There is a significant discrepancy between Herwig and Alpgen, and also between Pythia and MadGraph, for jets at central rapidity, and the discrepancy becomes greater as the jet p_T increases. Another example is the p_T of the second b quark (not from top decay) in t -channel single-top production. This second b arises from initial-state gluon splitting, $g \rightarrow b\bar{b}$; one b is transformed into a top quark by a t -channel W , and the other tends to reside at low p_T . The p_T and rapidity distributions of this second b differ significantly between a pure Matrix-Element calculation and a Matrix-Element plus PS calculation (Maltoni). This is dealt with in the best way we know how for single-top at the Tevatron, but we should be able to do better (Huseman). The same issue is present at the LHC (Chierici).

An area with a lot of current activity, that will also be important for the LHC, is W, Z production in association with heavy quarks (c, b). The first measurements from CDF and D0 of $W + c$ -jet are in rough agreement with NLO QCD, and it will be interesting to see how this evolves with more data (Harel). The CDF measurement of $Z + b$ -jet agrees well with NLO QCD at high p_T , but exceeds theory at low p_T (Glenzinski).

Given the large statistics for top-quark physics at the LHC, most measurements will be systematics limited. One idea to improve the jet energy scale at the LHC is to use the top-quark mass measured at the Tevatron as a constraint (Van Mulders and Bachacou). This is truly “TeV4LHC,” in the spirit of the workshop held in 2004-2005 [11].

7 New ideas for top

The previous sections already contain some new ideas for top, so this section is meant to capture ideas that didn't fit neatly elsewhere.

There are several theories beyond the standard model in which top-quark physics plays a special role. Those who believe in the standard Higgs model of electroweak symmetry breaking were accused of being “conventional,” a label that no particle physicist likes (Holdom). An alternative is to have the electroweak symmetry broken by a fourth generation of fermions and a new, strongly-interacting gauge interaction that acts on the third and fourth generations. This gives rise to both a heavy t' quark and a heavy X gauge boson that decays to $t\bar{t}$. A heavy object decaying to $t\bar{t}$ appears in many extensions of the standard model, and would manifest itself as a resonance in the $t\bar{t}$ invariant mass spectrum (Tait). The decay $t' \rightarrow Wq$ has been sought at the Tevatron, and a lower bound of 284 GeV (95% CL) has been placed on the t' mass by CDF (Sorin).

A classic standard-model effect in $t\bar{t}$ production that has yet to be confirmed is the correlation between the spins of the t and \bar{t} (Stal, Spiga, Veloso). The correlation differs between $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$, so a measurement of the spin correlation would allow one to extract the fraction of events from each production mechanism. Another method to extract this fraction is to study the underlying activity, which is expected to be greater for processes initiated by gluons. Using this technique, CDF has measured the fraction of events from $gg \rightarrow t\bar{t}$ to be consistent with zero (Pashapour).

Another standard-model effect that is being sought is the $t\bar{t}$ charge asymmetry (Pashapour, Shabalina). This asymmetry, present only for $q\bar{q} \rightarrow t\bar{t}$, is a difference between the rate at which top quarks and top antiquarks are produced at a given angle with respect to the incoming quark parton. It is a small effect because it arises first at NLO in QCD. At the Tevatron, it manifests itself as a forward-backward asymmetry of top quarks produced with respect to the proton beam. A recent measurement from D0,

$$A = (12 \pm 8 \text{ (stat)} \pm 1 \text{ (syst)})\% \text{ (D0)}$$

made in the $W + \geq 4$ jets mode, is consistent with the theoretical prediction of 4 – 5% [4].

Another asymmetry of interest is associated with the rapidity distribution of W^+ bosons, which are produced more in the proton direction than in the antiproton direction (Glenzinski). The agreement between theory and experiment is impressive, all the more so because this is one of the few places where we have a NNLO prediction as well as data of similar accuracy. Although this is often referred to as a charge asymmetry, it is of a completely different origin than the $t\bar{t}$ charge asymmetry discussed above, and is merely a consequence of the parton distribution functions. I find it preferable to call it a W rapidity asymmetry [12].

The production of a Higgs particle in association with $t\bar{t}$ at the LHC would give us a direct measurement of the top-quark Yukawa coupling to the Higgs (Aad and Steggemann). Followed by the decay $h \rightarrow b\bar{b}$, this signal is very challenging to extract from the backgrounds, but its importance makes it worth the effort. Even harder is to extract a signal for Higgs production in association with single top [13]. Perhaps one should attempt that first; then $t\bar{t}h$ will seem relatively easy!

We heard a variety of talks on searching for exotic top-quark physics at the Tevatron and the LHC (Sorin, Wicke, Yumiceva, Chevallier, Blekman and Milosavijevic). Along with $X \rightarrow t\bar{t}$ and t' mentioned above, there was discussion of top decay via a charged Higgs boson ($t \rightarrow h^+b$), flavor-changing neutral-current top decay ($t \rightarrow Zq, \gamma q$), and top squarks. We don't know which, if any, of these are realized in nature, but it does point out that we may very well find physics beyond the standard model by studying the top quark. We shall see.

8 Conclusion

This is an exciting time for top-quark physics, with data pouring out of the Tevatron experiments. We have seen a lot of new top-quark physics results over the past few years, most of which were presented at this workshop. The next few years will witness a continuation of the Tevatron program and the beginning of the LHC era. As exciting a time as it is, the best is yet to come!

Acknowledgments

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